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MELBOURNE, VICTORIA

REPORT

MRL-R-1111

ANALYSIS OF THE PERFORATION OF MONOLITHIC AND SIMPLE LAMINATE ALUMINIUM TARGETS AS A TEST OF ANALYTICAL DEFORMATION MODELS

R.L. Woodward and I.G. Crouch*

* Dr I.G. Crouch was a UK Exchange Scientist on attachment from the Royal Armament Research and Development Establishment, Chertsey, UK between February 1987 and June 1988.

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ABSTRACT

Several models are used to estimate the ballistic limit velocities of homogeneous aluminium targets impacted by small calibre armour piercing projectiles and blunt fragment simulators. It is demonstrated that a careful use of the models, combined with an understanding of material failure mechanisms, enables good estimates of ballistic resistance to be made using the analytical techniques. One of the techniques is modified and adapted to the calibration of ballistic resistance of simple two plate aluminium laminates. Correlation of computations with empirical data demonstrates that the technique is a useful design tool in predicting the optimum relative thicknesses of the two plates and the laminate performance.

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CONTENTS

ANALYSIS OF THE PERFORATION OF MONOLITHIC AND SIMPLE LAMINATE ALUMINIUM TARGETS AS A TEST OF ANALYTICAL DEFORMATION MODELS

1. INTRODUCTION

A number of analytical models have been developed at MRL which allow the computation of either depth of penetration or perforation velocity for the impact of projectiles on homogeneous metal targets. The models include one for the plugging of ductile metal targets by blunt, non-deforming projectiles [1] and others for the perforation of targets by pointed projectiles, where failure is by a ductile hole formation or dishing mode [2], by an adiabatic shear plugging mode [3] or by a discing mode where a scab of material is ejected from the rear of a target [4]. Many of these failure modes have been described and related to material characteristics and impact conditions [5]. Also developed were a model for deep penetration into a semi-infinite target by a deforming projectile [6,7,8], and a model to treat the dishing and plugging failure of thin targets impacted by blunt projectiles where the diameter is large in comparison with the plate thickness so that structural bending is significant [9,10]. This last model, DASH, has recently been applied to the impact of blunt missiles against thin targets [11].

Application of the above techniques to any particular situation requires an appreciation, based largely on experience, of the material characteristics, impact conditions, and expected failure modes. The availability of a consistent set of ballistic data on aluminium targets of a range of strengths, using two projectile types with the appearance of three distinct failure modes, [12], presented an opportunity to test some of the computational techniques and illustrate how an appreciation of likely behaviour can be used to adapt more than one method to some problems.

In addition to the above comparisons, one of the methods, that for plugging ductile metal targets [1], has been used, with some small modification, to estimate the response of simple, unbonded, two layer laminates. The approach provides a basis for the broader consideration of the behaviour of more complex laminates.

2. PERFORATION OF HOMOGENEOUS METAL TARGETS

(a) Pointed Projectiles

Figure 1 is a plot of relative ballistic limit against armour hardness for the perforation of aluminium targets by a small calibre armour piercing projectile [12]. The target thickness was approximately four times the armour piercing core diameter. Several aluminium alloys were used in standard tempers and re-heat treated conditions to provide data over a range of hardnesses. Two types of failure were observed and described as "segmenting"; a ductile failure mode in which the material is pushed to the side and often called ductile hole formation, and "discing"; where a disc of thickness approximately equal to the projectile diameter is ejected from the target rear.

For all of the models presented in references 1 to 8 the material characteristics can be fitted by curves of the form

$$\sigma = \sigma_o \epsilon^n \tag{1}$$

where σ_o and n are constants defining the strength and work hardening behaviour, respectively, of the metal, and σ and ϵ represent stress and strain. For the computations in this report, compression test data were available for four aluminium alloys in standard heat treated conditions. These values are listed in Table 1 along with corresponding hardness measurements.

The work done, (W), in ductile hole formation failure, which is the expected mode for a ductile target impacted by a pointed projectile, is given simply by [2,10]

$$W = \frac{\pi}{2} D^2 \sigma_o h_o \tag{2}$$

where D is projectile diameter and
h_o is target thickness.

Equating W to the kinetic energy of the armour piercing core of the projectile, allows a critical velocity for perforation to be calculated. Three points in Fig. 1, joined by a dashed line, show relative ballistic limits calculated using this method on the same scale. The simple analytical equation underestimates by less than 15% and the trend of the prediction, with hardness, is correct.

The empirical data shows a drop in performance above a hardness of 180 VPN due to the onset of discing failure. The 7001 T6 aluminium alloy is known to fail by discing [4] and a model for the discing mechanism gives an expression for the work done as

$$W = \frac{\pi}{2} D^2 \sigma_o (h_o - D) \quad (3)$$

This equation is a simplified version of that presented in reference [4] and ignores the work done in indenting the disc as well as various fracture energies, but will suffice for the approximations being examined here. It is also possible to use this equation to estimate the ballistic limit of a target which fails by discing. The point plotted at a lower level in Fig. 1 corresponding to a hardness of 210 VPN, indicates the magnitude of the expected drop in performance due to premature discing. The computation is of the correct magnitude. Unfortunately, no model is currently available to predict the target strength level at which discing will be observed, so one can only calculate the ballistic resistance for both the ductile and discing modes of failure and rely upon both experience and observation to decide which appropriate failure mode applies.

(b) Blunt Projectiles

Experimental data [12] for the relative ballistic limit for the perforation of aluminium targets by fragment simulating projectiles are plotted in Fig. 2 as a function of hardness. Generally these blunt penetrators force material ahead of them resulting in a plugging type failure except at the high hardness levels where scabbing was observed in the targets. The critical hardness for the onset of scabbing with the fragment simulators was similar to that found for the onset of discing with the pointed projectiles, Fig. 1. We may assume, therefore, that similar mechanisms are involved, as previously described by Woodward [5]. Three different modelling techniques are now used to estimate theoretical ballistic limits for this type of projectile/target interaction.

The first of these is a model developed by Woodward and de Morton [1] for the interaction of blunt non-deforming penetrators with ductile metal targets. The concept of the model and its sequence of events is illustrated in Fig. 3. The initial condititions, Fig. 3(a), involve impact of the projectile at velocity V_o with the target at rest. Thus a period of acceleration of material ahead of the projectile is required and this is illustrated in Fig. 3(b) as the first stage of the penetration process. During this first stage stress wave theory is used to treat acceleration of the material ahead of the projectile and the resisting force leads to deceleration of the projectile. This stage is complete when either the plug is ejected or the plug velocity V" equals the projectile velocity V' after which there is no velocity gradient and they move as a unit. During this first stage the velocity gradient across the plug results in its compression, material flows to the side, as indicated by the arrows in Fig. 3(b), and energy is dissipated in compression of the plug, shearing at the plug/plate interface and in frictional sliding between the projectile and the plate. In stage two, Fig. 3(c), once the plug and projectile velocities are equal, they slide as a unit, and work is done in shearing between the plug and target, further retarding the plug and projectile. Failure finally occurs when the plug loses contact with the plate. A computer program, which enables calculation using this model, "PLUG", is listed in Appendix 1 with typical input and output values. Two plugging failure computations were performed, and plotted as square points in Fig. 2, they show excellent agreement with the experimental plot.

Crouch [12] noted a small, but variable, amount of deformation of the fragment simulators during his perforation experiments. The questions which arise from

this work are:- (i) can we take this deformation into account since the plugging model assumes a rigid penetrator, and (ii) what difference is the small amount of deformation likely to make to the results? Several models are available for the perforation of metal targets by deforming projectiles. However, all of them require some post-perforation measurements of the target so that they are descriptive rather than predictive. Woodward [6,7,8] developed a model for deep penetration of a deforming projectile into a semi-infinite target, which is a simplified problem involving no "break-out" stage. The implementation of this model is described, and the computer program listed, in Reference [7]. By making some broad, radical approximations this deep penetration model is used below to estimate the perforation velocity for the finite thickness targets.

In the perforation of targets which are thick relative to the projectile diameter much of the work done, in the early stages, involves moving material to the side. It is also commonly observed that the final stages of penetration involve the ejection of a plug of thickness approximately equal to the projectile diameter. The ejection of the plug is a fracture process and the work done is small in comparison with that done in the early stages of penetration. With this in mind it was decided to use the deep penetration model to calculate the velocity required to penetrate a semi-infinite target to a depth, $h_o - D$, where h_o was our target thickness and D is the fragment diameter, and to compare this velocity with the critical velocity to perforate the plates. The two calculated points, represented by circles in Fig. 2, slightly overestimate the ballistic limit but the agreement with experiment is again excellent, especially given the radical assumption used in the model. In the present case the target thickness was approximately two calibres which would be near to the minimum for such a technique to work.

The third method used was simply to calculate the work done in plastic shearing of a plug and to equate this to the projectile kinetic energy. The work done in shearing a plug is given by the simple expression

$$W = \frac{\pi}{2\sqrt{3}} D h_o^2 \sigma_o \tag{4}$$

where the symbols have the same meaning as before. This expression is the one used for the second stage of the simple plugging model illustrated in Fig. 3(c) and is expected to give an underestimate of the work done [10]. Figure 2 shows the results joined by a broken line which is an underestimate of the order of 10 to 15%. The reason for using this simple equation is that it allows a calculation of the reduction in work done if the target failure is by scabbing. Assuming that the scab is ejected by the same mechanism as for the discing failure in Fig. 1, the expected scab thickness is one projectile diameter. If little work is done in actually ejecting the scab, the work done in penetration is equivalent to that for shearing the plug from a target of effective thickness (h_o - D). This is indicated by the calculation for 7001 aluminium (VPN = 210) in Fig. 2. The reduction in ballistic limit is of the same order as observed in Crouch's [12] empirical results.

It must be stressed that the assumption made to do the scabbing calculation is essentially in direct violation of the assumptions made above using the deep penetration problem to do a plugging calculation. Although there is no theoretical justification, the methods have a basis in experience and can be used to make estimates, only, of expected

response if used carefully. The correlations of Figs. 1 and 2 demonstrate what is possible with these relatively simple quantitative tools. It is also instructive to remember that when using the simple equations (2), (3) and (4) to calculate work done, a relatively large error may be somewhat masked when the data is presented in terms of a ballistic limit velocity, because of the square root function required to convert kinetic energy to velocity.

3. PERFORATION OF SIMPLE LAMINATES

Crouch [12, 13] has recently examined the potential of structural laminates in energy-absorping applications involving projectile impact. Against blunt-nosed penetrators [13] the potential benefit comes from preventing premature failure, by plugging, through the application of the crack-arrester principle. Instead of failure by a low-energy-absorbing shear process, more energy-absorbing mechanisms, like delamination and plastic bending, are encouraged.

In the perforation of laminated targets the most significant observations are debonding along one or more of the interlamellar joints and dishing of the rear of the target. Two supposed stages in the perforation of a laminated target are illustrated schematically in Fig. 4. As in the plugging model of Fig. 3, the first stage involves the acceleration of material ahead of the projectile as illustrated in Fig. 4(a). This stage may be treated in the same manner as simple plugging as long as material characteristics are well understood. During this stage it is generally seen that, near the projectile, shear separation may occur at the plug/target interface. However near the back of the target the laminate layers generally remain continuous during this stage. In the second stage, Fig. 4(b), where bending and stretching of the rear layers occurs, some model of dishing failure is required. Several approaches have been tried. The structural model DASH [9,10], which would be ideal for this analysis, cannot be used because its assumptions are violated when the target thickness exceeds one half of the projectile diameter, and in most cases it is generally observed that when the acceleration phase, Fig. 4(a), is complete, the thickness of target still to be perforated is approximately a projectile diameter. A simple analytical equation for dishing [2], which sums the work done in stretching and bending the target, has been shown to give reasonable estimates of behaviour over a large range of conditions [10]. The procedure, developed below, backs up the first stage of plugging with this dishing model to treat a simple two layer laminate; a case where no choice is required in deciding where any debonding occurs. Furthermore, in the case of a simple, unbonded, metal laminate, no new assumptions are required concerning uniaxial and shear flow stresses in relation to the simple stress/strain behaviour expressed in equation (1).

Figure 5(a) shows the situation at the end of the first stage of perforation of an homogeneous target (see Fig. 3(c)), while Figs. 5(b) and 5(c) show the two possible configurations at the end of the plug acceleration phase in the case of the simple laminate. L_B, L_F and L_C represent the displacement of the back of the plug, the displacement of the front of the plug and the residual contact length between plug and target respectively, after the stage of plug acceleration. T_I and T_E are the original thicknesses of laminate layers on the impact and exit sides of the target respectively.

In the case of simple plugging the simple model used in the computer program "PLUG" (see Appendix 1) calculates the work done in plug shearing as

$$W = \frac{\pi D \sigma_o}{2\sqrt{3}} L_C^2 \tag{5}$$

When treating the laminated target problem the plugging model was run and the impact velocity increased in small steps until the projectile just perforated the target. The output parameters include L_B, L_F, L_C and the energy represented by equation (5). If, instead of plugging, the rear plate is allowed to dish away, then the work done in dishing is given by [2,10]

$$W = \frac{\pi}{8} D \sigma_o T_E (D + \pi T_E) \tag{6}$$

For the case of Fig. 5(b) it is also necessary to include a term for the work done in shearing the residual ligament on the impact side, I, of the laminate. This term is

$$W = \frac{\pi D \sigma_o}{2\sqrt{3}} (T_I - L_B)^2 , \tag{7}$$

Simple corrections can then be made to the kinetic energy value obtained using PLUG. For case 5(b) this is done by subtracting the work calculated by equation (5) and adding that by equations (6) and (7). For case 5(c), where there is no residual ligament on the impact side, the treatment is identical, except that equation (7) becomes zero. This simple calculation is possible for a simple laminate. However, as the complexity of the laminate is increased not only will decisions be required as to where delamination occurs but also a simple correction method as adopted here could be misleading.

Yellup [14] produced data for impact of fragment simulating projectiles on a range of thicknesses of 2024 T351 aluminium in the form of homogeneous plates and unbonded, dual plate laminates. The data for the relative ballistic limit of homogeneous plates is shown in Fig. 6 as a continuous line over a range of plate thickness to projectile calibre ratios. Computations for plugging failure of homogeneous plates, using the program "PLUG", are shown by a dashed line. The agreement is good for the thicker targets but only moderate for thin targets.

Unlike the comparison presented in Figure 2, this simple laminate model underestimates the empirical data. On further examination, the two sets of data are not too different, for extrapolation of the two lines, to a target thickness equivalent of two calibres (ie. data in Fig. 2), brings the two sets of data into line. There are two possible reasons why the observed errors are greatest for the thinnest targets, both related to frictional terms. Firstly, in the model, PLUG, the first stage involves plug compression under heavily constrained conditions in which a significant amount of energy is assumed

to be absorbed through sticking friction: in thin targets, because of the reduced bulk of material, this term may be insignificant. Secondly, the expected gross bending of thin targets will significantly reduce the contact area, as already proposed by Crouch [13], between plug and target.

In Fig. 6 the performance of unbonded two plate laminates are plotted as points showing experimental data represented by a cross and computational results, using the above technique, shown by a circle. The number next to each point indicates the ratio of impact to exit plate thickness in the laminate. Despite the moderate agreement between the plugging model and experiment, at similar target thicknesses, the correction procedure for the laminates is seen to indicate correctly the magnitude and order of improvement expected over a monolithic target. Clearly the method developed is a useful first step in the quantitative understanding of the important responses within laminated targets. In section, these two-ply targets [14] showed failure by plugging of the plate on the impact side and stretching, bending and tearing of the exit plate as assumed in the model. Further work is continuing to extend these models to treat more complex laminates.

4. SUMMARY

Comparisons of calculated and empirical ballistic limit data for a range of aluminium target hardnesses and two projectile geometries, where several failure modes are observed, indicate that good estimates of performance are possible, provided our understanding of perforation mechanisms allows selection of the appropriate model. Some simple models are adapted to more complex problems, specifically a deep penetration model to examine the perforation of a finite thickness target, and a plugging model to handle a simple unbonded laminate where the rear plate fails in dishing. The latter approach opens the way to the treatment of more complex laminated targets.

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TABLE 1

Material Strength and Work Hardening Properties

Alloy Designation	σ_o (MPa)	n	Hardness (VPN)
5083 H15	452.	.113	105
7039 T6	638.	.075	155
7001 T6	964.	.088	210
2024-T351	776.	.096	135

APPENDIX 1

COMPUTER PROGRAM "PLUG" FOR SIMPLE PLUGGING MODEL

The input data for the program PLUG, which is a simple model solution for plugging failure, is in a file called PLIG.DAT. The data are set out below for the example of a 15 gram cylindrical penetrator of radius 9.5 mm impacting a steel target of thickness 20 mm at a velocity 1150 ms^{-1}. Standard values of Young's Modulus and density are used for the steel target. Experimental data are required for the target material parameters σ_o and n which represent target strength and work hardening rate respectively. To obtain σ_o and n, simple compression tests are performed on the target plate material and data at high strains are fitted to the relation

$$\sigma = \sigma_o \epsilon^n \tag{A.1}$$

where σ is the true stress and ϵ is the true strain. This is readily done as a straight line of slope n and intercept σ_o on logarithmic scales. The input file PLIG.DAT for the example problem is

PLIG.DAT	Symbol in Program PLUG	Physical Interpretation
7850.	RO	Target Density (kg/m^3)
206850.	E	Target Young's Modulus (MPa)
976.	SO	Target σ_o (MPa)
.263	EX	Target n
.0095	RAD	Projectile Radius (m)
.020	HO	Target Initial Thickness (m)
.015	ASS	Projectile Mass (kg)
1150.	VO	Projectile Velocity (m/s)

The data is accepted by the program PLUG which calculates a range of parameters and indicates whether perforation has or has not occurred. The output, PLOG.DAT, for the above example is:

```
 BA      CL      HT     STRN     WK        W        VN       V        T
.0102   .0098   .0120   0.515   5035.6    9205.8   310.1    308.3   .01399
.0102   .0098   .0120   0.515   5035.6   10815.7   310.1    136.9   .05777
 BA      CL      HT     STRN     WK        W        VN       V        T
 PERFORATION
 ENERGY          VEL
    9918.8      1150.0
```

All figures in the above output are in SI units for the appropriate quantity, except for time which is in milliseconds. The "Energy" figure is the initial projectile kinetic energy and, "VEL" refers to the initial projectile velocity. Other symbols are as follows:

Symbol in Output	**Quantity**
BA	Displacement of back of plug in first stage, (L_B in Fig. ~~8~~ 5)
CL	Contact Length Plug/Target at end of first stage, (L_C in Fig. ~~8~~ 5).
HT	Plug height.
STRN	Thickness strain in plug.
WK	Compressive work in first stage of deformation.
W Upper line	- total work in first stage
Lower line	- total work done in perforation.
VN	Velocity to which plug has accelerated in first stage.
V Upper line	- velocity of projectile at end of first stage
Lower line	- velocity of projectile/plug at exit.
T Upper line	- time for first stage
	- total time for perforation.

The details of the model are outlined in reference [1]. If the input velocity is sufficiently high then no second line appears in the output. In this case, well above the ballistic limit, the plug is ejected before it is accelerated to the projectile velocity because the plug/target contact length is reduced to zero. The program PLUG is listed below.

```
C     PLUG
C     PROGRAM TO CALCULATE PENETRATION PARAMETERS
C     WRITTEN BY RAYMOND L WOODWARD
C              MATERIALS RESEARCH LABORATORY,DSTO MELBOURNE
      OPEN(UNIT=1,FILE='PLIG',STATUS='OLD')
      OPEN(UNIT=2,FILE='PLOG',STATUS='NEW')
 21   FORMAT(F5.0/F7.0/F6.1/F5.3/F7.6/F7.6/F7.6/F6.1)
      READ(1,21)RO,E,SO,EX,RAD,HO,ASS,VO
 75   FORMAT(T4,'BA'T11,'CL'T18,'HT'T25,'STRN'T35,'WK'T48,'W'
     2T59,'VN'T68,'V'T76,'T')
      WRITE(2,75)
 77   FORMAT(2X,F5.4,2X,F5.4,2X,F5.4,2X,F6.3,2X,F8.1,5X,F8.1,
     35X,F5.1,2X,F5.1,1X,F6.5)
 79   FORMAT(2X,F10.1,4X,F6.1)
 81   FORMAT(T4,'ENERGY'T17,'VEL')
 82   FORMAT(T4,'PERFORATION')
 83   FORMAT(T4,'NOT THROUGH')
      SO=SO*1000000.
      E=E*1000000.
      Y=SO*((E/SO)**(EX/(EX-1)))
```

```
      C=(E/RO)**.5
      A=2.7*Y/(RO*C)
      B=((2.7*SO*EX/RO)**.5)*2/(EX+1)
      BB=B*((2.7*Y/E)**((EX+1)/2))
      EN=.5*ASS*(VO**2)
      VOL=3.1416*RAD**2*HO
      ST=Y/E
      STRN=ST*2.7
      WK=0
      BA=0
      DO 102 L=1,5000
      VN=B*STRN**((EX+1)/2)+A-BB
      F=VOL*2.7*SO*(STRN**EX)/HO
      HT=HO*EXP(-STRN)
      T=(HO-HT)*2/VO
      FR=VN*T/2
      BA1=(VO+VN)*T/2
      DBA=BA1-BA
      BA=BA1
      CL=HO-BA
      WK=WK+F*DBA
      WS=1.8138*RAD*SO*(HT*(HO-HT)+FR*(2*HT-FR))
      WF=(1.8183*SO*RAD*BA**2)
      W=WS+WF+WK
      V2=VO**2-2*W/ASS
      V=V2**.5
      T=T*1000
      IF(V.LE.VN)GO TO 99
      IF(CL.LE.0)GO TO 100
      STRN=STRN+ST
  102 CONTINUE
   99 WRITE(2,77)BA,CL,HT,STRN,WK,W,VN,V,T
      SASS=ASS+3.1416*RAD**2*HT*RO
      WS=1.8138*RAD*SO*CL**2
      W=W+WS
      V2=VN**2-2*WS/SASS
      IF(V2.LT.0)GO TO 202
      V=V2**.5
      T=T+2000*CL/(V+VN)
  100 WRITE(2,77)BA,CL,HT,STRN,WK,W,VN,V,T
      WRITE(2,75)
      WRITE(2,82)
      GO TO 203
  202 WRITE(2,83)
  203 WRITE(2,81)
      WRITE(2,79)EN,VO
      STOP
      END
```

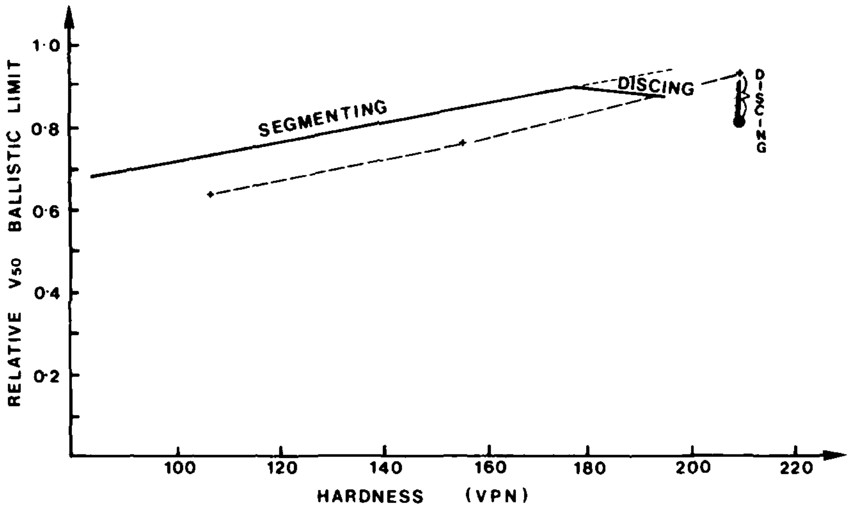

FIGURE 1 Plot of relative ballistic limit against aluminium target hardness for perforation by a small calibre armour piercing projectile. Empirical data [12] are represented by continuous line, computations by dashed line and points. Failure modes are indicated.

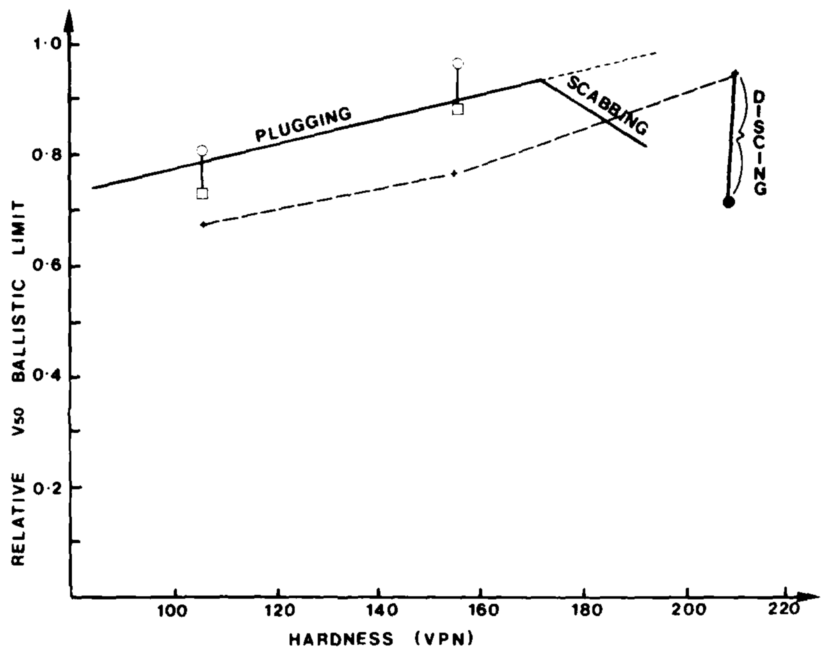

FIGURE 2 Plot of relative ballistic limit against target hardness for aluminium plates impacted by fragment simulating projectiles. Target thickness approximately twice the projectile calibre. Empirical data are represented by continuous line, computations by a dashed line and points. Failure modes are indicated.

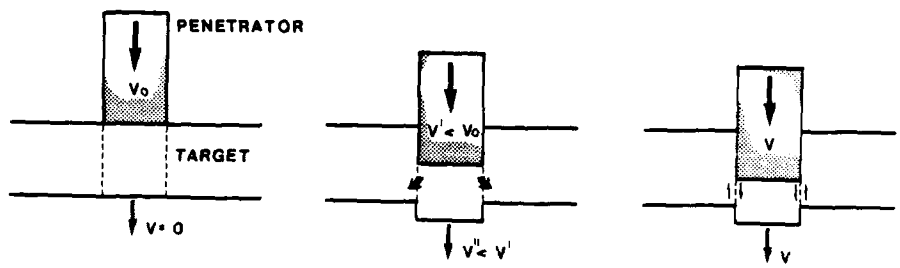

FIGURE 3 Sequence of stages in the plugging failure of a ductile metal target. (a) Initial Impact conditions, (b) first stage where the projectile is moving faster than the mean plug velocity and (c) second stage where projectile and plug move together with the plug shearing from the plate. Arrows in (b) indicate the directions of material motion.

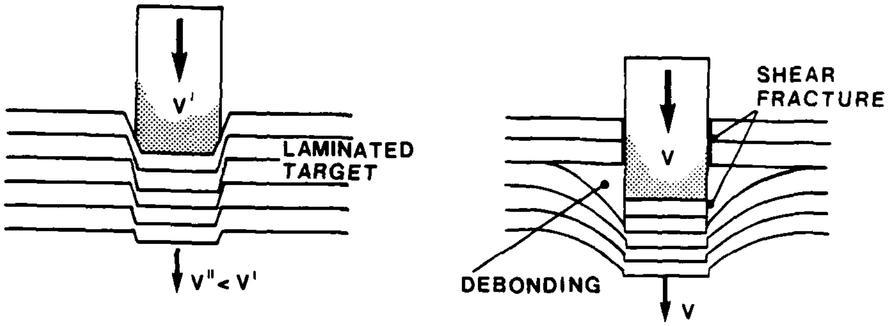

FIGURE 4 Simplified concept of the perforation of a laminated target. (a) Initial stage of plug acceleration and (b) debonding and bending deformation of the rear of the laminate.

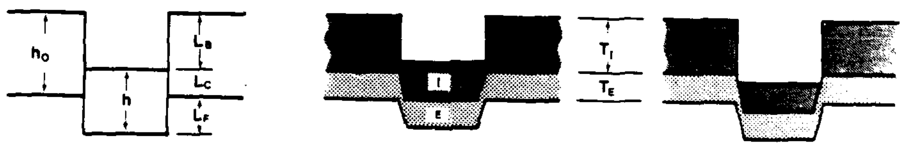

FIGURE 5 Model used to analyse a simple two plate laminate. (a) Situation at the end of plug acceleration, first stage, for simple plugging of a homogeneous plate and (b) and (c) two alternative possible corresponding conditions for a simple laminate at the end of the acceleration stage. I represents the impacted plate in the laminate and E represents the plate on the plug exit side. Other symbols are explained in the text.

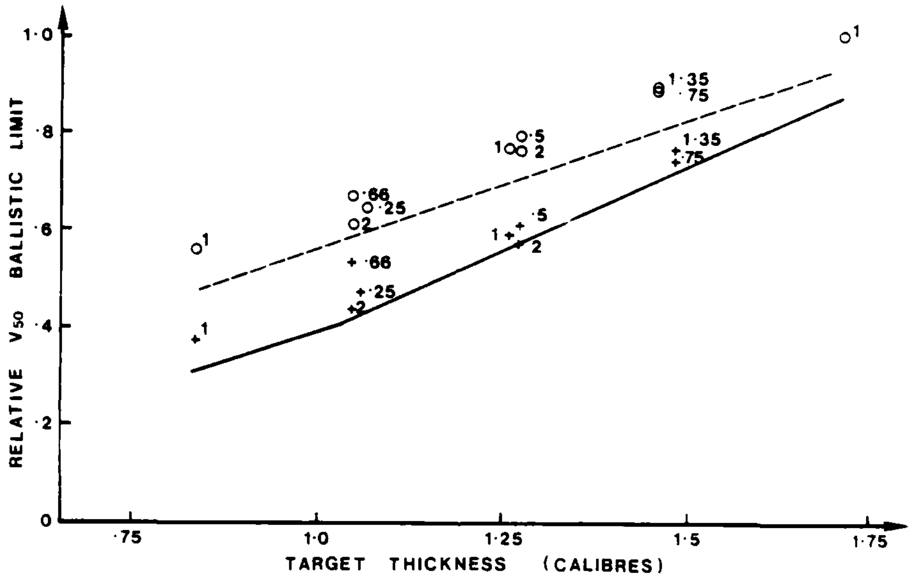

FIGURE 6 Relative ballistic limit as a function of target thickness (in projectile calibres) for impact of fragment simulators on homogeneous and laminated 2024 T351 aluminium targets. The lower continuous line represents empirical data and the upper dashed line computations for an homogeneous plate respectively. Crosses represent empirical data and circles, calculations, respectively, for laminated targets. The number indicates the relative impact to exit side plate thicknesses for each laminate.

DOCUMENT CONTROL DATA SHEET

REPORT NO.	AR NO.	REPORT SECURITY CLASSIFICATION
MRL-R-1111	AR-005-219	Unclassified

TITLE

Analysis of the perforation of monolithic and simple laminate aluminium targets as a test of analytical deformation models

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REPORT DATE	TASK NO.	SPONSOR
April 1988	ARM 87/137	Army

FILE NO.	REFERENCES	PAGES
G6/4/8-3529	14	21

CLASSIFICATION/LIMITATION REVIEW DATE

CLASSIFICATION/RELEASE AUTHORITY

Chief of Division,
Materials, MRL

SECONDARY DISTRIBUTION

Approved for Public Release

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Announcement of this report is unlimited

KEYWORDS

Aluminium
Models
Laminates
Terminal ballistics
Armor piercing ammunition
Armor
Failure mechanisms
Fragments
Penetration

SUBJECT GROUPS 0079E

ABSTRACT

Several models are used to estimate the ballistic limit velocities of homogeneous aluminium targets impacted by small calibre armour piercing projectiles and blunt fragment simulators. It is demonstrated that a careful use of the models, combined with an understanding of material failure mechanisms, enables good estimates of ballistic resistance to be made using the analytical techniques. One of the techniques is modified and adapted to the calibration of ballistic resistance of simple two plate aluminium laminates. Correlation of computations with empirical data demonstrates that the technique is a useful design tool in predicting the optimum relative thicknesses of the two plates and the laminate performance.